Supra–subduction zone extensional magmatism in Vermont and adjacent Quebec: Implications for early Paleozoic Appalachian tectonics

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ABSTRACT

Metadiabasic intrusions of the Mount Norris Intrusive Suite occur in fault-bounded lithotectonic packages containing Stowe, Moretown, and Cram Hill Formation lithologies in the northern Vermont Rowe-Hawley belt, a proposed Ordovician arc-trench gap above an east-dipping subduction zone. Rocks of the Mount Norris Intrusive Suite are characteristically massive and weakly foliated, have chilled margins, contain xenoliths, and have sharp contacts that both crosscut and are parallel to early structural fabrics in the host metasedimentary rocks. Although the mineral assemblage of the Mount Norris Intrusive Suite is albite + actinolite + epidote + chlorite + calcite + quartz, intergrowths of albite + actinolite are probably pseudomorphs after plagioclase + clinopyroxene. The metadiabases are subalkaline, tholeiitic, hypabyssal basalts with preserved ophitic texture. A backarc-basin tectonic setting for the intrusive suite is suggested by its LREE (light rare earth element) enrichment, negative Nb-Ta anomalies, and Ta/Yb vs. Th/Yb trends. Although no direct isotopic age data are available, the intrusions are broadly Ordovician because their contacts are clearly folded by the earliest Acadian (Silurian–Devonian) folds. Field evidence and geochemical data suggest compelling along-strike correlations with the Coburn Hill Volcanics of northern Vermont and the Bolton Igneous Group of southern Quebec. Isotopic and stratigraphic age constraints for the Bolton Igneous Group bracket these backarc magmas to the 477–458 Ma interval. A tectonic model that begins with east-dipping subduction and progresses to outboard west-dipping subduction after a syncollisional polarity reversal best explains the intrusion of deformed metamorphosed metasedimentary rocks by backarc magmas.

Keywords: metadiabases, supra–subduction zone, Rowe-Hawley belt, Dunnage zone, Bolton Igneous Group, Coburn Hill Volcanics, Mount Norris Intrusive Suite.

INTRODUCTION

The pre-Silurian tectonic belts of the northeastern Appalachians are composed of rocks that were deposited in an ancient ocean basin (Iapetus) that developed east of ancestral North America (Laurentia) during Late Proterozoic to Ordovician time; these rocks originated within the continental margin, main ocean basin, or supra–subduction zone (including forearc, arc, and backarc). In southern Quebec, these rocks are assigned to the Humber and Dunnage zones (Fig. 1) depending on whether they have continental-margin or oceanic (including supra–subduction zone) affinity, respectively (e.g., Williams, 1978). Rocks of the Dunnage zone were juxtaposed against those of the Humber zone during the Early to Middle Ordovician closure of Iapetus. The Dunnage zone and part of the easternmost Humber zone of southern Quebec connect along strike to the south with the northern Vermont Rowe-Hawley belt of New England. That belt has not been formally subdivided into continental and oceanic (including supra–subduction zone) domains as in southern Quebec because the belt, as a terrane, has been defined to include lithologies that were assembled in an arc-trench gap tectonic setting (e.g., Stanley and Ratcliffe, 1985) during the closure of Iapetus. Thus, the belt contains elements of both southern Quebec zones.

The bedrock geology of the northern Vermont Rowe-Hawley belt occupies a critical position in the northern Appalachian orogen because it links well-preserved early Paleozoic ophiolite and accretionary-wedge sequences in southern Quebec with correlative rocks in New England. Pre-Silurian metadiabasic intrusions of the Mount Norris Intrusive Suite, found within specific metasedimentary thrust slices in the Rowe-Hawley belt, are particularly important links. These intrusions have a supra–subduction zone geochemical signature and, thus, also provide crucial information about the tectonic setting of the New England and Quebec Appalachians during Ordovician (Taconic) orogenesis. The purpose of this paper is to describe the geologic setting and geochemistry of the Mount Norris Intrusive Suite metadiabases in northern Vermont, make correlations with analogous mafic rocks in Vermont and southern Quebec, and formulate tectonic models for the region on the basis of these data and other geologic constraints.

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GSA Bulletin; December 2003; v. 115; no. 12; p. 1552–1569; 11 figures; 3 tables.
SUPRA–SUBDUCTION ZONE MAGMATISM IN APPALACHIANS OF VERMONT AND ADJACENT QUEBEC

REGIONAL GEOLOGIC SETTING

Western Vermont exposes continental-margin rocks deformed by collision of a volcanic arc with the ancient Laurentian continent during closure of segments of the Early Paleozoic Iapetus Ocean (Stanley and Ratcliffe, 1985; Rankin, 1994). Precambrian (Laurentian) basement makes up the core of the Green Mountains. Carbonate and clastic rocks in western Vermont represent an early Paleozoic continental-shelf sequence (Fig. 1).

A sequence of rift-related clastic rocks of Late Proterozoic to early Paleozoic age is preserved in a group of thrust sheets, called the Green Mountain slices (Fig. 1). Oceanic and supra-subduction zone rocks occur in the Rowe and the Moretown and Hawley slices, known collectively as the Rowe-Hawley belt. The belt in Vermont includes the Ottauquechee, Stowe, Moretown, and Cram Hill Formations in the northern half of the state; intrusive and extrusive rocks of the Barnard Gneiss and North River Igneous Suite (Armstrong, 1995; Ratcliffe et al., 1998) are part of the Rowe-Hawley belt in the southern half of Vermont. The Connecticut Valley Sequence lies to the east of the belt and consists mainly of Silurian and Devonian rocks. Although the Rowe-Hawley belt and Green Mountain slices were first deformed and metamorphosed during the Ordovician Taconic orogeny, the overprint from the Silurian–Devonian Acadian orogeny varies in intensity from modest to severe and generally increases in intensity to the east and in the vicinity of Acadian faults.

The Mount Norris Intrusive Suite crops out in part of the Rowe-Hawley belt; in particular, representatives of the suite appear most frequently in the Stowe and Moretown Formations (Fig. 2). Tectonic models for the Rowe-Hawley belt in New England (e.g., Stanley and Ratcliffe, 1985; Stanley and Hatch, 1988; Kim and Jacobi, 1996) generally portray the Stowe and Ottauquechee Formations as distal continental-shelf or rise sedimentary deposits that were incorporated into an accretionary prism during eastward-dipping subduction in the Ordovician, whereas the Moretown and Cram Hill Formations were situated to the east of the accretionary prism and were intruded by arc-source magmas in a supra-subduction zone setting.

LOCAL GEOLOGIC SETTING

The field area covering the northern Vermont Rowe-Hawley belt extends from the Vermont-Quebec border southward to the latitude of the Town of Morrisville and is bounded to the west by the Burgess Branch fault zone and to the east by the Richardson Memorial Contact, a major unconformity separating pre-Silurian from Silurian–Devonian rocks (Fig. 2). The northern Vermont Rowe-Hawley belt consists primarily of metasedimentary and metaigneous rocks from the Ottauquechee, Stowe, Moretown (western and eastern members), and Cram Hill Formations (lithologic descriptions are given in Fig. 2). The Belvidere Mountain, Tillotson Peak, and Worcester structural complexes are also considered to be part of the northern Vermont Rowe-Hawley belt.

Ottauquechee (Co) and Stowe Formation (Cs) rocks are commonly juxtaposed with one another in fault-bounded lithotectonic packages. Likewise, Moretown (Owm, Om) and Cram Hill Formation (Ocr) lithologies form lithotectonic packages. Ultramafic rocks in the northern Vermont Rowe-Hawley belt occur only in lithotectonic packages containing Ottauquechee, Stowe, and Moretown Formation rocks. Rowe-Hawley belt rocks sit structurally...
Lithotectonic packages that contain Mount Norris Intrusive Suite:

- Csmn: Stowe Fm. - Mt. Norris member
  - green phyllites
- Owm: Moretown Fm. - Western member
  - bluish-gray metasiltstones + black phyllites
- Om: Moretown Fm. - Eastern member
  - interbedded green "pinstriped" phyllites and granofels
- Ocr: Cram Hill Fm. - black phyllites and granofels, gray quartzites

LEGEND

- g: Silurian? granite+granodiorite
- Sdt: Diorite+Trondhjemite
- Sgb: Glenbrook Group
  - argillite + calcareous siltstone
- Omg: Magog Group
  - slate + felsic tuffs
- C7bh: Bunker Hill sandstone
- Osd: St. Daniel Fm-melange + Vermont correlatives
- Ocr: Cram Hill Fm.
  - black phyllites + quartzites
- U: Serpentinitized ultramafics
- greenstones:
  - Cambrian + Ordovician
- amphibolites:
  - Cambrian + Ordovician
- Corg: Ottauquechee Fm phylitic greywacke member
- Cex: Ottauquechee Fm
  - black phyllite member
- Es: Stowe Fm
  - Elmire Schist member
- Cslm: Stowe Fm,
  - interlayered black + green phyllite member
- Cx: Stowe Fm + Cj: Jay Fm
  - green phyllite member
- C2f: Fayston + C2z: Underhill
  - Fm green aitlic schists
- C2zh: Hazens Notch Fm
  - carbonaceous aitlic schists
- C2zg: Hazens Notch Fm
  - Albite Gneiss
above albite porphyroblast-bearing rocks of Hazens Notch (ζZhn) and Fayston (ζZf) Formations (Thompson and Thompson, 2003) as well as the intervening Belvidere Mountain (ophiolitic) and Tillotson Peak (blueschist-bearing) mafic complexes (Laird et al., 1984; Gale, 1986; Kim et al., 2001; Laird et al., 2001). The base of the Rowe-Hawley belt has been interpreted to be the Taconic-age Prospect Rock Fault (Fig. 2)—a west-directed thrust (Thompson et al., 1999; Thompson and Thompson, 2003). The Burgess Branch fault zone (Fig. 2) is a steeply east-dipping down-to-the-east normal fault of presumed Silurian age that reactivated an earlier thrust surface (Kim et al., 1999); detailed microstructural analysis has verified the normal-fault interpretation (Lamon and Doolan, 2001). The name “Burgess Branch fault zone” has supplanted the name “Belvidere Mountain Fault zone” of Stanley et al. (1984) (Kim et al., 1999). The Belvidere Mountain Fault zone was specifically redefined to represent only the sole thrust at the base of the Belvidere Mountain Complex (Kim et al., 1999). The Eden Notch Fault zone, of uncertain age, is a steeply west-dipping fault surface with equivocal slip direction (Fig. 2).

Detailed mapping has delineated fault-bounded lithotectonic packages that contain Mount Norris Intrusive Suite metadiabases in the study area (Stanley et al., 1984; Kim, 1997; Kim et al., 1998, 1999) (Fig. 2). None of the metadiabase-bearing slices is found east of the unconformity between pre-Silurian and Silurian–Devonian rocks (Richardson Memorial contact). Ultramafic bodies are found in fault contact with metadiabase-bearing lithologies in some locations.

A geologic cross section modified from Kim et al. (1999) (Fig. 3) shows that the metadiabases are found only in fault-bounded Stowe (ζsmn), Moretown (Om, Owm), and Cram Hill (Ocr) lithologies that lie at the highest structural levels. Similarly, a cross section modified from R.S. Stanley (1990, personal commun.) across the northern part of the study area shows that the metadiabases occur in the same Stowe and Moretown (western member) lithologies (Fig. 4A); however, instead of lying at the highest structural level, these lithotectonic packages were emplaced along early faults and subsequently were complexly folded with Ottauquechee Formation lithologies (ζO). The metadiabases do not have a uniform distribution throughout any individual lithotectonic package. For example, Figure 4B shows the distribution of individual metadiabase bodies in the Big Falls synform represented in the cross section of Figure 4A (Stanley et al., 1984; Evans, 1994).

**STRUCTURAL GEOLOGY AND METAMORPHISM**

The field area (Fig. 2) lies in the overlap zone between Taconic and Acadian structural fabrics, and the rocks have generally been subjected to biotite-grade metamorphism, although the Belvidere Mountain, Tillotson Peak, and Worcester Complexes have undergone garnet and higher grades of metamorphism (Laird et al., 1984, 2001). The dominant foliation west of the Burgess Branch fault zone is a generally steeply east-dipping Ta-
conic S1-S2 composite foliation that has been folded by gently plunging asymmetric F3 folds (Green Mountain folds) with a locally developed steeply west-dipping crenulation cleavage (S3). East of the Burgess Branch fault zone, the dominant foliation is a composite S2/S3 fabric in which S2 has been reoriented into the attitude of S3 and has been overprinted by a strongly developed S3 spaced cleavage (Kim et al., 1999). The S3 cleavage is known to be Silurian-Devonian because this cleavage can be traced across strike into Silurian-Devonian rocks where it is the earliest cleavage.

In the northern Vermont Rowe-Hawley belt, 40Ar/39Ar total-fusion ages on amphiboles indicate that the age of the Taconic metamorphism generally ranges from 471 to 460 Ma, whereas muscovite and biotite total-fusion ages indicate that the Acadian metamorphism ranges in age from 386 to 355 Ma (Laird et al., 1984, 1993). These data are consistent with the suggestion that the S1/S2 composite fabric is probably 471-460 Ma in age and the S3 fabric is probably 386-355 Ma in age.

Laird et al. (1993) obtained an 40Ar/39Ar plateau age of 505 ± 2 Ma on barroisitic amphibole from the Belvidere Mountain Complex amphibolite; this age implies that this amphibolite was deformed and metamorphosed prior to juxtaposition with the surrounding metasedimentary rocks at ca. 470-460 Ma. A total-fusion age of 468 ± 6 Ma on glaucophane from the adjacent blueschist-bearing Tillotson Peak Complex was reported by Laird et al. (1984).

Recent comprehensive 40Ar/39Ar work on more than 100 samples in southern Quebec indicates that metamorphic ages on muscovite and amphiboles range from 469 to 460 Ma in the Dunage zone and from 430 to 411 Ma in the internal part of the Humber zone (Castonguay et al., 2001). The separation between the two metamorphic-age domains is the Silurian, down-to-the-east, St. Joseph normal fault, which is locally coincident with the Baie-Verte-Brompton Line that separates Dunage zone from Humber zone rocks (Williams and St-Julien, 1982; Castonguay et al., 2001). The oldest metamorphic ages in the Dunage zone are associated with the S1-S2 composite foliation generated by east-over-west thrusting, whereas the Silurian ages are associated with S3, which is either a west-over-east backthrust-related fabric or down-to-the-east normal-fault fabric. Both the Dunage and easternmost part of the Humber zones are also affected by
Silurian–Devonian (Acadian) deformation and metamorphism.

DESCRIPTION OF MOUNT NORRIS INTRUSIVE SUITE

Field Relationships

The Mount Norris Intrusive Suite metadiabases are characteristically gray, massive, rounded, granular, weakly foliated rocks with distinct buff-colored weathering rinds. Some, but not all, metadiabases have plagioclase phenocrysts (Fig. 5). Fresh metadiabase surfaces commonly have secondary calcite. An intrusive origin is based on the presence of chilled margins, rare xenoliths of metasedimentary lithologies, and sharp contacts with surrounding metasedimentary units. The metadiabase contacts may be either coplanar with the dominant foliation (Fig. 5A) or cut it at some angle (Fig. 5B). At one location in the western member of the Moretown Formation metasedimentary rocks (Owm), a large (5 m wide) metadiabase dike in the metasiltstones cuts the earliest recognizable composite foliation (probably Taconic) at a high angle (Fig. 5B); this early foliation is folded by the Acadian F3 upright asymmetric folds. Intrusion of the dikes/sills is always clearly pre-S3 (Acadian) and therefore is pre- or syn-S2 (Fig. 5A). The metadiabases are frequently boudinaged within the dominant foliation (Taconic S2) such that individual dikes/sills can usually not be traced on the ground over large distances. The boudinage indicates that the original contact relationship between the metadiabases and the host metasedimentary rocks can be obscured because the contact may have been rotated into parallelism with the dominant foliation. The metadiabases do not cross any known fault.

Mineral Assemblage

Although highly altered, the metadiabases exhibit an ophitic texture that is observable both in outcrop and hand sample. In thin section, the ophitic texture manifests itself as intergrowths of albite + actinolite that may be pseudomorphs after plagioclase + clinopyroxene. In many instances, the plagioclase has been replaced by epidote. The overall mineral assemblage of the metadiabases is albite + actinolite + epidote + chlorite + calcite + quartz (Dick, 1989; Evans, 1994; Kim and Coish, 2001).

AGE

Regional Age Information

There are no igneous crystallization ages for any igneous units in the study area, so along-strike extrapolation is necessary to establish age control. The minimum age for the Moretown Formation in southern Vermont has been established by 496 ± 8 Ma and 486 ± 3 Ma U-Pb zircon ages on a trondhjemitic and a tonalitic intrusion, respectively (Ratcliffe et al., 1997). A metafelsite within the Cram Hill Formation in southern Vermont has been dated at 484 ± 4 Ma by U-Pb in zircon (Ratcliffe et al., 1997).

In the Dunnage zone of Quebec, the along-strike counterpart to part of the northern Vermont Rowe-Hawley belt, the U-Pb zircon age of plagiogranites in the Thetford Mines and Mount Orford ophiolites is 479 +3/-2 Ma (Dunning and Pedersen, 1988) and 504 ± 3 Ma (David and Marquis, 1994), respectively. More recently acquired U-Pb zircon ages of granitoids in the Thetford Mines ophiolite are 469 ± 4 Ma and 470 +5/-3 Ma (Whitehead et al., 2000). Metahyolites from the Ascot Complex yielded U-Pb zircon ages of 441 ±7/ -12 and 460 ± 3 Ma (David and Marquis, 1994).

Doolan et al. (1982) traced black and gray slates interbedded with pillow and massive greenstones that are part of the St. Daniel Formation mélangé in southern Quebec across the international border into Vermont where they are mapped as part of the Cram Hill Formation and Coburn Hill Volcanics, respectively. Although there is no fossil age control in the northern Vermont Rowe-Hawley belt, there are zone 12 graptolites (ca. 458 Ma on the 1999 Geological Society of America Time Scale) near the base of the Magog Group in southern Quebec (Berry, 1962; Harwood and Berry, 1967). Because the Magog Group unconformably overlies the St. Daniel Formation mélangé in southern Quebec (Cousineau, 1990), the mélangé is ostensibly pre–Late Ordovician in age. In addition, the St. Daniel Formation unconformably overlies the ca. 477 Ma (obduction age) Thetford Mines ophiolite.
TABLE 1. MAJOR AND TRACE ELEMENT DATA FOR METADIBASE DIKES OF THE MOUNT NORRIS INTRUSIVE SUITE, NORTHERN VERMONT

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KIM et al.
The Umbrella Hill conglomerate member (Ormu—Fig. 2) of the Moretown Formation is a deformed and metamorphosed polymict quartz-cobble and metamorphic-rock-fragment conglomerate with a phyllic matrix (e.g., Badger, 1979) that unconformably overlies lithotectonic packages containing Stowe and Ottauquechee Formation rocks (Fig. 2). Kim et al. (1999) interpreted this unconformable contact to be faulted (and called it the Umbrella Hill Fault zone). Under the assumption of east-facing stratigraphic continuity, early workers interpreted the Umbrella Hill conglomerate member to be the base of the Moretown Formation (Konig and Dennis, 1964). Recent mapping, however, shows that it is interlayered to the east with green phyllites (Ombh) that are truncated by the Coburn Hill Volcanics; these interrelationships indicate a general equivalence in stratigraphic position with both the Coburn Hill Volcanics and St. Daniel and Crum Hill Formations.

**Age of the Mount Norris Intrusive Suite**

Although the metadiabases cannot be dated directly, the following criteria strongly support a pre-Silurian age: (1) The metadiabases either cut or are parallel to the earliest foliations (Ordovician) in the Stowe and Moretown Formation rocks. (2) The metadiabases are confined to distinct fault-bounded thrust slices in the northern Vermont Rowe-Hawley belt. Where exposed, the faults that border the thrust slices are folded by the earliest Silurian-Devonian (F3) folds. (3) The earliest Acadian-age (F3) folds closely fold the metadiabases. (4) The metadiabases do not cut faults of any age. (5) The metadiabases are folded by pre-F3 folds in the Big Falls synform area of northern Vermont (Stanley et al., 1984). (6) The metadiabases are not found in any Silurian-Devonian metasedimentary rocks to the east.

**GEOCHEMISTRY**

**Analytical Methods**

Samples selected for analysis were as fresh and unweathered, homogeneous, and free of significant veining as possible. Samples were cut into ~2 cm cubes with a water-cooled saw, air dried, passed through a ceramic jaw crusher, and powdered in a shatterbox. The powders were ignited at 1000 °C in graphite crucibles and were fused and dissolved via lithium metaborate methods (Coish and Sinton, 1992). Concentrations of the 10 major elements (SiO₂, Al₂O₃, TiO₂, MgO, Fe₂O₃, CaO, Na₂O, K₂O, MnO, and P₂O₅) and concentrations of Cr, Ni, V, and Sc were determined on a Jarrell Ash ICP-OES (inductively coupled plasma–optical emission spectrometer) unit at Union College, Schenectady, New York. All geochemical data were shown in Tables 1 and 2. Analytical accuracy was evaluated by running U.S. Geological Survey standards as unknowns before and after each 10-sample run (Table 3).

**Chemical Mobility**

Metamorphic mineral assemblages in the metadiabases and surrounding metasedimentary rocks indicate that, in the study area, the Rowe-Hawley belt underwent lower greenschist-facies metamorphism that reached a maximum of biotite grade (Laird et al., 1984). Because the primary mineral assemblage of the metadiabases has been severely altered and lost-on-ignition (LOI) values are relatively high, chemical effects of alteration should be evaluated prior to presenting petrogenetic and tectonic interpretations.
Several researchers have shown that major elements such as K\textsubscript{2}O, Na\textsubscript{2}O, MgO, CaO, and SiO\textsubscript{2} and trace elements such as Rb, Sr, and Ba are mobile during seawater-influenced metasomatism (e.g., Humphris and Thompson, 1978; Mottl, 1983; Wilson, 1989). In an effort to evaluate major element mobility, we utilized a method that calculates a numerical index of alteration = 100[(MgO + K\textsubscript{2}O)/ (MgO + K\textsubscript{2}O + CaO + NaO)] where indices of 36 ± 8 represent relatively unaltered rocks (Hashiguchi et al., 1983). The index of alteration for the 53 Mount Norris Intrusive Suite metadiabase samples ranges from 31.3 to 42 (average = 35.6; median = 35.5; standard deviation = 2.8). Thus, none of the metadiabases falls outside the unaltered envelope in this method.

An alternative method to evaluate mobility is to plot elements against a high field strength element (HFSE), such as Zr, not thought to be mobile during metamorphism (e.g., Floyd and Winchester, 1978; Pearce and Norry, 1979; Rollinson, 1993). Strong linear trends on such diagrams indicate relative immobility of the element. Key elements—Th, Nb, Ce, and Y—used in petrogenetic interpretations were plotted against the immobile element Zr in order to evaluate their mobility (Fig. 6). Although there is some scatter in the plots, a strong positive linear trend for the majority of the samples probably directly reflects the original igneous fractionation processes. If metasomatic alteration significantly affected these HFSEs, one would not expect such a distinct linear pattern for these incompatible elements. Furthermore, as seen in the following sections, the geochemical groups maintain their integrity throughout the various discrimination methods.

Th is thought to be mobile under some circumstances (Mélançon et al., 1997) but is an important chemical discriminant. In the Mount Norris Intrusive Suite samples, it forms linear trends with Zr (Fig. 6) and also with Ce and Nb (not shown); furthermore, there is no correlation between LOI and Th, indicating no systematic variation with alteration. Finally, in discrimination diagrams used in later sections, Th plots in tight groupings typical of petrologically related igneous rocks. Thus, we consider Th to have been relatively immobile during metamorphism of the Mount Norris Intrusive Suite rocks.

Classification

SiO\textsubscript{2} concentrations in the metadiabases range from 48% to 56%, indicating that the rocks may be basaltic to basaltic andesite in composition (Table 1). Because SiO\textsubscript{2} is mobile during metamorphism, other classification schemes using immobile elements are more reliable for metavolcanic rocks. Accordingly, we use the Zr/TiO\textsubscript{2} vs. Nb/Y diagram (Floyd and Winchester, 1978) and the alkali index vs. Al\textsubscript{2}O\textsubscript{3} plot (Middlemost, 1975) to classify the Mount Norris Intrusive Suite samples (Figs. 7A, 7B). The general coherence of the Mount Norris samples in these classification diagrams suggests that these elements have not been greatly affected by metamorphic alteration; hence the diagrams may be used to determine igneous origins. From the Zr/TiO\textsubscript{2} vs. Nb/Y diagram, we conclude that the Mount Norris samples are subalkaline basalts (Fig. 7A). Subalkaline basalts can be further classified as tholeiitic or calc-alkaline basalts. Clearly, the Mount Norris Intrusive Suite samples are tholeiitic basalts (Fig. 7B).

Geochemical Characteristics of Mount Norris Intrusive Suite Rocks

Although all samples from the suite are basalts or basaltic andesites, there is some variation in major and trace element chemistry. Samples range from fairly primitive basalts (MgO = 8.5%, Ni = 160 ppm, Cr = 400 ppm) to fractionated basalts (MgO = 4.3%, Ni = 35 ppm, Cr = 50 ppm). Furthermore, there are systematic trends from the most primitive to the most fractionated samples; specifically, Ni, Cr, and Ca decrease with increasing MgO, whereas Ti, P, Fe, Zr, and Y increase. These trends are typical of fractionation of early-formed minerals, such as olivine, pyroxene, and/or plagioclase, from basaltic magmas.

The rare earth element abundances are also typical of basalts; light rare earth element (LREE) abundances are between 20 and 40 times chondritic abundances, whereas heavy rare earth elements (HREEs) range from 10 to 20 times chondritic abundances (Fig. 8A). The LREE patterns show enrichment in LREE, display flat HREE abundances, and have slight negative Eu anomalies (Fig. 8A). The negative Eu anomalies likely reflect the fractionation of plagioclase. Relative to mid-ocean ridge basalts (MORBs), the Mount Norris Intrusive Suite samples have highly irregular LILE
(large ion lithophile element) abundances, which are indicative of significant metasomatic alteration; also, the samples have distinctive negative Ta and Nb anomalies and generally flat patterns, near or above unity, for elements P to Yb in Figure 8B.

**Tectonic Environment Inferred from Geochemistry**

Geochemical fingerprints in ancient mafic rocks are not always diagnostic, but can be suggestive, of tectonic environment. In this section, normalized-element diagrams and tectonic-discrimination diagrams are used to suggest a tectonic environment that is shown herein to be consistent with the geology of the region.

Mafic rocks with slightly LREE-enriched patterns, as shown by the Mount Norris Intrusive Suite rocks, can be found in various tectonic settings such as backarc basins (BAB; Fig. 8A) or, more broadly, supra±subduction zone (SSZ) basins, continental rifts, and certain enriched mid-ocean ridge (E-MORB) environments. On MORB-normalized extended-element diagrams (e.g., Fig. 8B), patterns with negative Ta-Nb anomalies relative to adjacent Th and Ce, however, suggest involvement of a mantle source that has been affected by subduction. Marginal basins (interarc, backarc, forearc) are perhaps the most common environment for eruption of volcanic rocks with such characteristics. Specifically, basalts from marginal basins are chemically similar to mid-ocean ridge basalts, except many marginal-basin basalts show enrichment in LILEs, depletion in Al and Ti, negative Nb-Ta anomalies, and higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for a given $^{143}\text{Nd}/^{144}\text{Nd}$ ratio relative to MORB (e.g., Keller et al., 1992; Hawkins, 1995; Leat et al., 2000). In detail, marginal-basin basalts are not all alike but rather exhibit a range of compositions. For example, in the northern section of the Mariana Trough, basalts vary from MORB-like in mature spreading areas in southern regions to those indistinguishable...
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Figure 7. (A) Mount Norris Intrusive Suite data plotted on Zr/TiO$_2$ vs. Nb/Y discrimination diagram (Floyd and Winchester, 1978). Note that all samples are subalkaline basalts. (B) In an alkali index [$AI = (Na_2O + K_2O)/((SiO_2-43) \times 0.17)$] vs. Al$_2$O$_3$ discrimination diagram (Middlemost, 1975), the Mount Norris Intrusive Suite rocks mostly plot as tholeiitic basalts.

from island-arc basalts in the north where spreading is incipient (Gribble et al., 1996, 1998). Likewise, in the Scotia Sea, backarc volcanic compositions vary in detail with location along the spreading-center segments, but in general, samples have slightly enriched LREE abundances (relative to their HREE abundances) with small or no Ta-Nb anomalies (Leat et al., 2000). One factor called on to explain compositional variation of backarc basalts is the amount of subduction component added to depleted subarc mantle; the subduction component can be delivered in fluids or as partial melts from the subducting plate. The amount of the subduction component added may be controlled by the proximity of the subducting plate to the site of marginal-basin spreading, which in turn may be related to the maturity of the basin; early stages of spreading may produce magmas indistinguishable from island-arc volcanic rocks, whereas once spreading becomes established, subduction-related components become less abundant.

Following from the foregoing discussion, the negative Nb-Ta anomalies coupled with the flat MORB-normalized abundances of the elements from P to Yb (in Fig. 8B) in Mount Norris Intrusive Suite metadiabases suggest the tectonic environment of a SSZ basin. In fact, their overall concentrations of HFSEs and negative Ta-Nb anomalies are similar to those characteristics in many basaltic rocks from western Pacific marginal basins (Figs. 8A and 8B). Neither the Nb-Ta anomalies nor the LREE enrichment is extreme. This fact may indicate that the metadiabases formed in a mature rather than an incipient SSZ basin (Allan and Gorton, 1992) but not so mature as to produce MORBs without any subduction-zone signature.

Tectonic-discrimination plots of Mount Norris Intrusive Suite samples are also consistent with their origin in a marginal basin. In most tectonic-discrimination diagrams, modern marginal-basin basalts plot in the same field as mid-ocean ridge basalts or in the overlap fields between island-arc tholeiites and marginal-basin basalts. Rocks from the Mount Norris Intrusive Suite also consistently plot in MORB or BABB (backarc-basin basalt) fields in many discrimination diagrams (e.g., Fig. 9A). A small number of samples fall in the arc field, further suggesting a connection with a subduction environment.

The Ta/Yb vs. Th/Yb diagram (Pearce, 1983) can be used to more convincingly show the presence of a subduction component in volcanic rocks. Mafic samples derived from the mantle and unaffected by later processes fall within a mixing zone (array) between a depleted-mantle source (DMS = MORB) and an enriched-mantle source (EMS = oceanic-island basalt [OIB] source) (two parallel lines in Fig. 9B). Subsequent igneous processes and/or the introduction of contaminants will drive a sample away from the mixing array (Fig. 9B): S represents the direction a magma composition moves by addition of a subduction component, C represents the addition of a continental-crust component, f represents fractional crystallization, and W represents within-plate source variations. Although two of the Mount Norris Intrusive Suite metadiabase samples plot within the mixing array, the majority of samples plot above the mixing array in a region that may indicate the addition of a subduction component in either an oceanic island-arc or active continental-margin tectonic setting. The fact that some samples plot in the oceanic island-arc (OIA) field or in the overlap zone between the oceanic island-arc field and active continental-margin (ACM) field makes a subduction component more likely and thus consistent with a backarc-basin origin for the metadiabases.

Summary of Geochemistry

The Mount Norris Intrusive Suite metadiabases in the Rowe-Hawley belt of northern Vermont are tholeiitic, basaltic, hypabyssal intrusions. Because it is difficult to distinguish chemically among mid-ocean-ridge, backarc-basin, and island-arc basalts, more than one interpretation of the tectonic origin of the Mount Norris Intrusive Suite is possible. However, the following geochemical criteria strongly indicate an origin in a supra-subduction zone: (1) negative Ta-Nb anomalies on MORB-normalized spider diagrams, (2) displacement along a subduction trajectory away from a normal-mantle mixing trend in a Ta/
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REGIONAL GEOCHEMICAL AND TECTONIC CONTEXT

The Mount Norris Intrusive Suite mafic basic intrusions can be correlated to rocks north and south along strike. To the south in central Vermont, mafic basic intrusions occur in the Rowe–Hawley belt (Cua, 1989; Martin, 1994); however, limited geochemical work precludes detailed comparison with the Mount Norris Intrusive Suite. To the north, the Coburn Hill Volcanics in northern Vermont (Gale, 1980; Evans, 1994) and the Bolton Igneous Group in southern Quebec (Cady et al., 1963) may be equivalents, albeit extrusive rather than intrusive. If the Mount Norris Intrusive Suite mafic basic intrusions are considered collectively with these along-strike correlatives, then the magmatic episode was regionally extensive, and not merely an isolated igneous event, in the northeastern Appalachians. It is thus important to examine these correlatives and make the case on field, geochemical, and geochronologic grounds that the Mount Norris Intrusive Suite should be considered as equivalent.

Coburn Hill Volcanics

The Coburn Hill Volcanics, situated on the eastern side of the Rowe–Hawley belt in northern Vermont (Fig. 2), are a thick sequence of pillowled greenstones of presumed Ordovician age in stratigraphic contact with black phyllites that locally have breccia horizons. These mafic rocks were originally called the Bolton Igneous Group (Doll, 1951), but later were mapped as the Coburn Hill Member of the Moretown Formation and were stratigraphically correlated with the Bolton Igneous Group of southern Quebec (Cady et al., 1963). Doolan et al. (1982) demonstrated that both the black phyllites and the associated mafic rocks of the Coburn Hill Volcanics in northern Vermont can be mapped continuously northward into the respective black “slates” of the St. Daniel Formation and Bolton Igneous Group mafic metavolcanic rocks of southern Quebec (Fig. 2). Although the Mount Norris Intrusive Suite mafic basic intrusions are found within lithotectonic packages that lie to the south and west of the Coburn Hill Volcanics and associated black phyllites, all these rocks are thought to be correlative (Kim et al., 1999; Kim and Coish, 2001) because (1) Coburn Hill Volcanics and interlayered Cran Hill Formation black phyllites have been mapped continuously southward into black phyllites (also classified as Cran Hill) that contain mafic basic intrusions (Fig. 2) and (2) bluish-gray metasandstones found in slices of the western member of the Moretown Formation to the west are also intimately associated with Cran Hill black phyllites to the east (Gale, 1980); the slices of the western member of the Moretown Formation probably root to the east in the Cran Hill Formation.

On the basis of major and trace element geochemistry, Gale (1980) and Evans (1994) determined that the Coburn Hill Volcanics (called Bolton volcanics by Evans) were tholeiitic to calc-alkaline basalts. A representative tectonic-discrimination diagram using their data shows that the mafic rocks of the Coburn Hill Volcanics have an ocean-floor (MORB or BABB) affinity (Fig. 10A). Evans (1994) showed that these metabasalts have LREE-enriched patterns and spider-diagram patterns with significantly elevated Th (7–8 times MORB) abundances, elevated Ce (≈2 times MORB), and flat patterns from P to Yb (in Fig. 10B). Their trace element patterns (Evans, 1994) are nearly identical to those of the Mount Norris Intrusive Suite mafic basic intrusions (Fig. 10B); however, Nb was not analyzed by Evans (1994) and thus a critical component cannot be compared. Nevertheless, on the Ta/Yb vs. Th/Yb diagram (Fig. 9B), the two samples of Evans (1994) plot within the grouping of Mount Norris Intrusive Suite samples, near the overlap zone between oceanic island arcs and active continental margins.

Bolton Igneous Group

As previously discussed, the mafic rocks of the Bolton Igneous Group of southern Quebec are a northern continuation of the Coburn Hill Volcanics of northern Vermont (Gale, 1980; Doolan et al., 1982) (Fig. 2). The contact re-
relationship between the Bolton mafic rocks and the surrounding St. Daniel Formation mélangé can be stratigraphic or tectonic. Doolan et al. (1982) observed conformable contacts with interbedding of mafic metavolcanic rocks and black phyllites over short distances. Because the Bolton mafic bodies have highly sheared contacts with the surrounding St. Daniel Formation mélangé and because they lack feeder dikes, Mélancçon et al. (1997) concluded that the Bolton mafic rocks were fault-bounded tectonic blocks. Furthermore, ultramafic slivers juxtaposed with Bolton mafic bodies also suggest tectonic contacts (Stanley et al., 1984).

Although there are no direct age constraints on the mafic rocks of the Bolton Igneous Group, there are isotopic and stratigraphic age constraints on units adjacent to the St. Daniel Formation mélangé. The mélangé unconformably overlies the Thetford Mines ophiolite (e.g., Schroetter et al., 2001, 2002) and stratigraphically (unconformably) underlies the Late Ordovician Magog Formation (e.g., Doolan et al., 1982). Because a 479 Ma U-Pb zircon age on a plagiogranite constrains the age of crystallization of the Thetford Mines ophiolite (Dunning and Pedersen, 1988) and a 477 ± 5 Ma Ar/Ar age on amphibole in the metamorphic sole of the ophiolite constrains the date of obduction (Whitehead et al., 1996), the base of the unconformably overlying the St. Daniel Formation mélangé is ostensibly younger than 477 Ma. Biostratigraphic control (graptolites) suggests that the base of the Magog is Caradocian or approximately pre–Late Ordovician (e.g., Berry, 1962). Thus, the Bolton mafic rocks are essentially bracketed in the age interval from 479 to 458 Ma. If the correlation between the Mount Norris Intrusive Suite mafic rocks and the Bolton Igneous Group and Coburn Hill Volcanics is correct, then the Mount Norris is also pre–Late Ordovician. The case for correlation is strengthened by comparing the geochemistry of the Bolton mafic rocks with the Mount Norris diabases.

Mafic rocks of the Bolton Igneous Group of Quebec (Mélancçon et al., 1997) exhibit trace element geochemical signatures nearly identical to those of the northern Vermont Mount Norris Intrusive Suite mafic rocks (Fig. 10B). The Bolton mafic samples are LREE enriched, and their MORB-normalized spider diagrams show a negative Ta-Nb anomaly relative to Th and Ce. Ti vs. Zr (not shown) and Zr vs. Zr/Y tectonic-discrimination diagrams also show that the Bolton Igneous Group rocks plot in MORB or BABB fields. Figure 9B—a Ta/Yb vs. Th/Yb diagram—shows that the Bolton Igneous Group mafic rocks also plot above the mantle mixing array along a subduction-signature trend suggesting a SSZ basin origin for the Bolton Igneous Group. Also on the Ta/Yb vs. Th/Yb diagram, the field defined by the Bolton samples overlaps with Mount Norris Intrusive Suite and Coburn Hill Volcanics samples.

Mélancçon et al. (1997) interpreted the mafic rocks of the Bolton Igneous Group to have formed as transitional MORB in the Iapetus Ocean, but acknowledged that they could also be backarc related. The St. Daniel Formation mélangé is currently interpreted to have been deposited in a “piggyback” basin unconformably overlying the Thetford Mines ophiolite (e.g., Schroetter et al., 2001, 2002; Tremblay et al., 2001) rather than in an accretionary prism tectonic setting. This interpretation favors a backarc or, more generally, an SSZ basin origin for the Bolton Igneous Group.

Summary of Correlations

The Mount Norris Intrusive Suite intrusions can be correlated with the Coburn Hill Volcanics in northern Vermont and the Bolton Igneous Group in southern Quebec on the basis of similar stratigraphy and geochemistry. First, the Mount Norris is correlated with the Coburn Hill mainly because of their identical geochemistry but also because they both lie in the highest structural slices in the region. Second, the Coburn Hill can be directly linked to the Bolton rocks because outcrops can be traced between the two. Third, black phyllite units interbedded with the Coburn Hill Volcanics in the Cram Hill Formation of Vermont
Figure 10. (A) Zr vs. Zr/Y diagram used to compare Mount Norris Intrusive Suite data (gray field) with Coburn Hill Volcanics data (Gale, 1980; Evans, 1994) and Bolton Igneous Group (BIG and Bolton Mountain) (Melançon et al., 1997). (B) MORB-normalized (Pearce, 1982) spider diagram plotting selected Bolton Igneous Group (BIG) mafic rocks (Melançon et al., 1997) compared to Bolton Mountain, Vermont, data (Evans, 1994) and the Mount Norris Intrusive Suite (MNIS) rocks.

can be traced into phyllites interbedded with the Bolton in the St. Daniel Formation mélangé of southern Quebec. Finally, by using age information from southern Quebec, we infer that the Mount Norris Intrusive Suite—Bolton Igneous Group—Coburn Hill Volcanics were formed in the Middle Ordovician, between the obduction of the Thetford Mines ophiolite at 477 Ma (Whitehead et al., 1996) and the deposition of the base of the Magog Formation at ca. 458 Ma (Berry, 1962).

TECTONIC MODELS

Regional Considerations

It is generally accepted that the Late Proterozoic–early Paleozoic Iapetus Ocean began to close through subduction in the Late Cambrian. This closure culminated in an arc-continent collision by which parts of the passive-margin sequence, Laurentian base-

ment, early rift-facies rocks, and oceanic and supra-subduction zone terranes were thrust westward over autochthonous passive-margin sedimentary rocks—i.e., what is called the Taconic orogeny. Most existing tectonic models (e.g., Stanley and Ratcliffe, 1985; Pinet and Tremblay, 1995; Karabinos et al., 1998) begin with eastward-directed subduction; however, there is controversy over the duration and polarity of the subduction zone(s) that led to the Taconic orogeny. The controversy focuses on whether there was protracted evolution of a single arc system (Bronson Hill arc) above an east-dipping subduction zone (Stanley and Ratcliffe, 1985) or two independent arcs wherein the first arc (Early Ordovician Shelburne Falls arc) developed above an east-dipping subduction zone and the second arc (Late Ordovician Bronson Hill arc) developed above a west-dipping subduction zone (Karabinos et al., 1998). In the single-arc model, arc volcanism lasted from ca. 500 Ma until 440 Ma and continued past the time of arc-continent collision (ca. 450 Ma) (Stanley and Ratcliffe, 1985; Ratcliffe et al., 1998). In the two-arc model, eastward-directed subduction resulted in arc-continent collision at ca. 470–460 Ma and was followed by a reversal in subduction polarity and construction of the Bronson Hill arc above a west-dipping subduction zone (Karabinos et al., 1998). Alternatively, other workers have proposed that the Bronson Hill arc was built off the coast of Gondwana on the east side of Iapetus and accreted to Laurentia in the Late Ordovician (van Staal et al., 1998). Following accretion of the arc(s) to Laurentia in the Late Ordovician, the Iapetus Ocean continued to close and eventually Laurentia collided with the Avalon microcontinent in the Devonian (Acadian orogeny).

Although “Taconic” arc magmatism in the northeastern Appalachians spanned from ca. 505 to ca. 440 Ma, there appear to have been different pulses of arc magmatism that correspond to different tectonic events. The oldest arc magmas, generated from the initiation of eastward-directed subduction outboard of Laurentia (Baie-Verte oceanic tract of van Staal et al. [1998]), ranged from ca. 505 Ma to ca. 490 Ma and include the Mount Orford ophiolite at 504 Ma (David and Marquis, 1994), the 496 Ma Barnard Gneiss of the Rowe-Hawley belt in southern Vermont (Ratcliffe et al., 1998), and the Coastal Complex of Newfoundland at 505 Ma (Jenner et al., 1991) (Fig. 11). Several workers have proposed that after the arc system became established, a major episode of forearc extension occurred to generate boninitic magmas (Hibbard, 1983; Bédard and Kim, 2002; Kim and Jacobi, 2002). Examples are found in the Betts Cove ophiolite (488 Ma—Dunning and Krogh, 1985; Coish, 1989; Bédard et al., 1998), Bay of Islands Complex (484 Ma—Jenner et al., 1991), and Thetford Mines ophiolite (479 Ma—Dunning and Pedersen, 1988) (Fig. 11). After obduction of the Thetford Mines ophiolite at ca. 477 Ma (Whitehead et al., 1996) and during deposition of the overlying St. Daniel Formation mélangé in a proposed “piggyback” basin environment (Schroetter et al., 2001, 2002), the Mount Norris Intrusive Suite—Bolton Igneous Group—Coburn Hill Volcanics story begins.

TECTONIC MODELS FOR ORIGIN OF MOUNT NORRIS INTRUSIVE SUITE

Any tectonic model to explain the origin of the Mount Norris Intrusive Suite should account for (1) production of magma with a
Figure 11. Possible models for the tectonic setting of the Mount Norris Intrusive Suite (MNIS) metadiabases (and Bolton Igneous Group [BIG]). See text for discussion.

Given these restrictions and the foregoing regional magmatic and tectonic context, we present three possible models to explain the origin of the Mount Norris Intrusive Suite: (1) intrusion in a backarc associated with east-dipping subduction (Fig. 11, model A1), (2) intrusion following slab breakoff (collisional delamination) (Fig. 11, model A2), and (3) intrusion in a backarc associated with west-dipping subduction (Fig. 11, model A3). We argue the merits of each model and provide reasons why we prefer model A3.

In model A1, the Mount Norris Intrusive Suite–Bolton Igneous Group–Coburn Hill Volcanics magmas were generated at a backarc spreading center and intruded into Moretown, Stowe, and Cram Hill Formation sedimentary rocks behind an early island arc developed above an eastward-dipping subduction zone (Fig. 11, model A1). Thrust sheets from the backarc would have to be deformed, metamorphosed, and transported westward during arc-continent collision. A shortcoming of model A1 is that field evidence indicates that the Mount Norris Intrusive Suite cuts Taconic foliations internal to the thrust slices that contain them or that have xenoliths of foliated metasedimentary rock indicating that the host rocks were deformed and metamorphosed prior to intrusion. With the exception of the accretionary prism, supra–subduction zone (forearc, arc, and backarc) regions generally behave quite rigidly and are not significantly ductilely deformed prior to orogenesis (Hamilton, 1988). The accretionary prism can be intruded by arc magmas only if significant trench rollback has occurred (C.R. van Staal, 2003, personal commun.) or if the angle of subduction is nearly vertical. Furthermore, prior to arc-continent collision, the arc region is extensional, not compressive (e.g., Hamilton, 1988). Once arc-continent collision begins, however, convergence may be translated from the forearc and trench region to the backarc and result in the formation of backarc/retro-arc thrusts (Silver et al., 1983; Rangin et al., 1995). Only if the Mount Norris Intrusive

supra–subduction zone (backarc) geochemical signature, (2) intrusion of the magma into thrust slices containing already-deformed lithologies, and (3) transportation of the Mount Norris Intrusive Suite westward along thrust sheets.
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this suture along the east side of the Connecticut Valley synclinorium. Furthermore, van Staal et al. (1998) interpreted the Ascot Complex (460–441 Ma) of southern Quebec to represent the arc above this westward-dipping subduction zone. In this scenario, the Mount Norris Intrusive Suite–Bolton Igneous Group–Coburn Hill Volcanics would have formed in a backarc tectonic environment behind the Ascot arc.

Recent geochronologic data from southern Quebec support model A3. Isolated 470–469 Ma granitoids that intruded the peridotite of the Thetford Mines ophiolite (Whitehead et al., 2000) indicate that some felsic magmatism postdated the obduction of the ophiolite at 477 Ma. Whitehead et al. (2000) suggested that these granitoid magmas could have been “derived by melting of the Laurentian margin over a west-dipping subduction zone or by shear heating at the base of an obducting ophiolite nappe” (p. 926).

Although we think that each of the tectonic models proposed herein for the Mount Norris Intrusive Suite–Bolton Igneous Group–Coburn Hill Volcanics have merits and pitfalls, we think that the subduction-polarity-reversal model (Fig. 11, model A3) best accommodates the field and geochemical constraints. Variations of this model have been proposed both by van Staal et al. (1998) and Karabinos et al. (1998). Hamilton (1988) elaborated about his work in the Pacific that “long-continuing, steady-state subduction systems are atypical; that complex sequences of collison, aggregation, reversal, and internal deformation are the rule; and that aggregates of collided bits can be assembled far from their final resting places” (p. 1518). The subduction-polarity-reversal model allows intrusion of supra-subduction zone magmas into deformed and metamorphosed thrusts slices by turning the former outer forearc region and collision zone into a backarc. In this model, the Mount Norris Intrusive Suite–Bolton Igneous Group–Coburn Hill Volcanics are backarc intrusions and volcanic rocks that formed roughly coevally with the Ascot Complex arc and forearc igneous rocks.

CONCLUSIONS

Five general conclusions result from a detailed field and geochemical study of the Mount Norris Intrusive Suite: (1) Mafic rocks of the Mount Norris Intrusive Suite intruded metamorphosed sedimentary rocks during the Early–Middle Ordovician, probably sometime between 480 and 460 Ma. (2) The intrusions were tholeitic basalts that were metamorphosed to greenschist facies and deformed to varying degrees; remnant igneous textures are preserved in many samples. (3) Geochemistry indicates that the basalts may have formed in an extensional region (marginal basin) of a supra-subduction zone environment; Nb-Ta anomalies, Th/Yb relationships, and the abundance patterns of REEs indicate that their source was probably depleted mantle modified by a subduction component. (4) Rocks of the Mount Norris Intrusive Suite are correlated with the Coburn Hill Volcanics in Vermont and the Bolton Igneous Group in Quebec on the basis of stratigraphy and geochemistry. (5) Although several tectonic models are plausible, the conclusion that the intrusions are subduction-related tholeiitic basalts that cut metamorphosed and deformed sedimentary rocks leads to a preferred model in which westward-directed subduction resulted in the development of extensional basins in terranes accreted to Laurentia by earlier eastward-directed subduction.

ACKNOWLEDGMENTS

We thank the Vermont Geological Survey for the funding to conduct some of the geochemical analyses described herein. We also thank Kurt Hollocher of Union College for running the prepared samples on his ICP-MS unit; Marjorie Gale, Peter Thompson, Rolfe Stanley, and Barry Doolan for the numerous discussions associated with the production of the new Vermont State bedrock map; and David West for much discussion and an incisive review of an early draft. Jim Hibbard, Sheila Seaman, and Cees van Staal helped improve the manuscript with perceptive and thorough formal reviews.

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